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Through What Factors does Polymer Concrete have Mechanical Resistance?

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Abstract
Polymer as an option to achieve this goal (improvement of concrete properties) has been considered for several decades. Polymer materials are used in both ways to improve the properties of concrete. Solid and hardened polymer materials in the form of fibers (such as polypropylene) or FRP rebars reinforce concrete. The process of polymerization and hardening is carried out in manufacturing factories, and materials with specific characteristics are provided to the user. Boron, carbon, glass, and polyamide are the most important materials from which fibers are made. Carbon FRP (CFRP) and glass (GFRP) rebars are made of fibers with a matrix of polymeric materials (such as epoxy). In addition to the use of fibers (polymer composites) in civil engineering in other fields such as aerospace engineering (making shuttles), transportation (making cars and airplanes), sports goods (making rackets and ski sticks), machinery and tools (turbine blades, gears), etc. are used. Non-solid polymer materials can be used to improve the quality of concrete. These materials harden during concrete processing and improve the resistance properties of concrete by forming networks intertwined with the cement network. Polymer injection concrete (PIC) and polymer cement concrete (PCC) are among these. The type of polymer and its mixing percentage are very effective on the final strength of concrete. Active research and development of concrete-polymer composites in Germany, America, England, Japan, and Russia began approximately 80 years ago and now they are widely used in various applications. For example, the volume of polymer used only in polymer-cement mortar (PCC) in Japan at the end of the 20th century has reached more than 100,000 tons per year.

Keywords: Polymer, Cement, FRP, Carbon Bars, Polyamide

1. Introduction

Concrete is one of the most widely used construction materials, which is widely used due to its low price, ease of use, and ability to respond to the required conditions. From the time of the use of concrete by the Romans until 1824 and the manufacture of Portland cement by Joseph Spadin, especially in recent centuries, people sought to improve the properties of concrete and used adhesives, additives, and various stone materials to achieve their goals (Norouzian M. M., *et al*., 2024) [31]. Today, there is a wide range of materials and methods to improve the properties of cement concrete (Portland cement concrete) or to replace the use of cement in concrete, depending on the required mechanical and chemical resistance and structural issues and existing conditions, according to the costs (Norouzian, M. M., 2024) [31].

Improvement of concrete properties in two general ways: Reinforcing concrete using fibers and rebar, mainly to improve the bending strength and ductility of concrete. Improving the quality of concrete itself is done by adding chemicals, pozzolans, and fillers. In general, the reasons for expanding the use of composite structures are:

- Efficiency, which causes beautiful architecture to arise in the building
- Resistance to weather conditions
- Corrosion resistance in corrosive environments.

Buildings where the use of metal is not allowed (Kahvand, M., *et al*., 2015) [20].

Polymer concrete (PC) is one of the forms of non-solid use of polymer in concrete, which does not improve the quality of concrete (cement), but has a sticky polymer binder that replaces cement and holds stone materials together after hardening. Polymer concrete has much higher resistance properties than cement concrete and can be a good substitute for it if concrete (cement) is unable to provide the necessary resistance (Sadigh Sarabi, M., *et al*., 2024d) [35]. Application in structural members with high compressive and especially tensile strength, as well as low permeability and high chemical resistance, makes it a suitable option for building structures on coasts, cold regions, water and sewage channels, and water and chemical tanks. Having high damping (about four times that of steel) has led to its use in making a bed for mechanical devices and machines with high vibration (Naghibi Iravani, S., *et al*., 2024a) [28].

In addition to the above advantages, having impact and abrasion resistance, etc., brings many practical fields, including road construction and bridge covering for concrete and polymer materials (Norouzian & Gheitarani, 2024) [32]. However, the expensiveness of polymer materials, weakness against high temperatures, being toxic to some extent, or having environmental problems for some polymers or processing agents (hardeners or hardeners) or additives can be considered as its disadvantages and weaknesses (Gheitarani, N., *et al*., 2024a). Due to earthquake proneness and the high cost and time of construction in our country, the use of prefabricated and light materials is strongly felt in the construction industry (Sadigh Sarabi, M., *et al*., 2023b). Technology that has been used for years in advanced countries, especially America. Lightness, high mechanical and chemical resistance, and low processing time are the effects of using polymer materials in these products (Gheitarani, N., *et al*., 2020) [16].

The use of polystyrene foams in block beam ceilings and prefabricated walls is growing in Iran. Polymers have different types and characteristics and are divided into two groups: Thermoset (hard heat) and thermoplastic (soft heat). Usually, thermoset polymers are used in making polymer concrete. However, most of the polymers used in concrete are thermoplastic polymer-cement. Criteria such as hardening at room temperature, fire resistance, environmental issues, and economic issues are placed next to mechanical properties and guide consumers to choose a polymer from among all types of polymers (Dizaji, A. A., 2024a) [10]. According to extensive tests and research conducted by researchers about polymer concrete, depending on the type and amount of polymer materials (resin and hardener) and additives, there are wide changes in the amount of strength and outstanding characteristics of polymer concrete. For example, the value of compressive strength in polymer concrete can be between 50 and 160 megapascals. Therefore, in this thesis, an attempt has been made to study the factors affecting the strength of polymer concrete (especially the compressive and bending strengths).

2. Theoretical

Cement concrete. Concrete consists of a cementitious binder with aggregates that require water to harden. The mechanical properties of concrete are affected by the properties of the cement composition, the type and size of the aggregate, the amount and quality of water, temperature, humidity, and curing (Dehghan S., 2024a) [7]. The hydration of cement particles in the presence of water results in the formation of a hard and strong network that surrounds the aggregates. The following is a brief description of the components and strength properties of cement concrete (Karimimansoob *et al*., 2024b) [22].

***Cement*:** Cement is obtained by mixing calcareous materials with materials containing silica, aluminum, and iron oxides (such as clay) and baking them to the clinker stage. Cement compounds hydrate in the presence of water and produce C3S2H3 and calcium hydroxide. The C3S2H3 compound is the main factor in setting cement (Zaker Haghighi *et al*., 2014) [43].

***Aggregate*:** It constitutes about 75% of the volume of concrete. Aggregates are classified into different groups based on the type of constituent minerals, appearance, and surface texture. Given that the stresses on the contact surface of a grain may be higher than the compressive stress, the required strength for aggregates must be higher than the strength of concrete (the strength of a suitable aggregate reaches about 80 MPa). The presence of organic matter, salt impurities, and clay or very fine particles in the aggregate hurts concrete (Aghazadeh, M. *et al*., 2018) [3].

***Water*:** It is used to hydrate cement and create a setting, and is also effective in improving efficiency and creating better density. Water whose pH is between 6 and 8 and does not have a salty taste is suitable for use in concrete (Karimimansoob *et al*., 2024a) [21]. The water in concrete is divided into three parts: Mixing water, gel water, and capillary pore water. With an increase in the water-cement ratio, capillary pores are added, which increases the strength of concrete.

***Pozzolan*:** Materials that do not have setting and cementing properties on their own. But in the presence of water, they react with calcium hydroxide resulting from hydration and form compounds with cementitious properties. Volcanic ash, baked clay, and fly ash are among the pozzolans used in concrete (Dehghan S. *et al*., 2024).

Properties of cement concrete (Portland cement concrete):

***Compressive strength*:** Almost all properties of concrete are related to the compressive strength of concrete, and with increasing compressive strength, tensile, flexural, abrasion, fatigue, permeability, etc. of concrete increase nonlinearly (Aghazadeh, M. *et al*., 2019) [1].

Therefore, compressive strength is a good criterion for expressing the quality of concrete (Dizaji, A. *et al*., 2023) [11]. The strength of concrete is a function of time and increases with time, and this increase initially has a more upward trend (Sadigh Sarabi, M., *et al*., 2024a) [36]. For samples with different cement compositions, the strengths obtained at equal times are different (Sohrabi, S., 2024a) [42]. For example, C3A increases the early-age strength of concrete, but this compound produces calcium sulfoaluminate in the presence of sulfate, which is harmful to concrete. Therefore, this compound is less used in anti-sulfate cement, and this action has caused this type of cement to set slowly (Naghibi Iravani, S., *et al*., 2024b) [29].

***Tensile and flexural strength*:** Tensile strength increases with increasing compressive strength at a lower rate. For low-strength concrete, the ratio of tensile strength to compressive strength is approximately, which decreases with increasing compressive strength**.** One of the factors affecting this ratio is moisture (Naghibi Iravani, S., *et al*., 2024c) [30].

The compressive strength of concrete in the dry state is greater than in the wet state, but the tensile (direct) strength does not change much. Although the direct tensile strength is not greatly affected by aggregates, the flexural strength of concrete increases with angular aggregates (Sadigh Sarabi, M., *et al*., 2024c) [37]. Among the methods for calculating tensile strength, the flexural method provides greater resistance than the direct and spiral methods (Norouzian & Gheitarani, 2023) [27].

Modulus of elasticity: A function of the type of aggregate, the ratio of aggregate to cement, and the strength of concrete. Moisture increases the modulus of elasticity by about a few gigapascals (unlike compressive strength). The range of the modulus of elasticity of concrete is between 15 and 35 GPa, with the higher values of this range being for very high-strength concrete. In addition, the modulus of elasticity of aggregates such as sand and granite is about 40 GPa, and basalt and rounded quartz are more than 80 GPa (Aghazadeh, M. *et al*., 2017) [2].

Fatigue resistance: When concrete is subjected to a stress of about 70 to 80 percent of its short-term strength, the joining of tiny cracks in the concrete over time causes the concrete to fail (static fatigue). Also, if the concrete is subjected to loading cycles, its fatigue resistance decreases with an increasing number of cycles, and the rate of decrease for compressive fatigue resistance is greater than for tensile fatigue resistance (relative to short-term strength) (Sadigh Sarabi, M. 2024) [34]. As the compressive strength of the concrete increases, its fatigue resistance increases. Concrete breaks at half its compressive strength after approximately one million loading cycles (Gheitarany, N., *et al*., 2013b).

Impact strength: Although impact strength usually increases with increasing compressive strength (less energy is absorbed per impact), this strength is more affected by tensile strength and, in particular, the type of aggregate. Concrete containing crushed aggregate shows better strength. It is necessary to note that strength also increases with increasing loading rates in concrete specimen tests (Dizaji, A. A. 2024b) [9].

Shrinkage: Shrinkage is caused by hydration, drying, and carbonation. The water-to-cement ratio, the volume of cement paste to aggregate, the type of aggregate, and the moisture content affect the shrinkage of a concrete piece. The maximum shrinkage (drying and carbonation) of a typical concrete piece is about 1600×6-10 (Farrokhirad & Gheitarani, 2024) [12].

Permeability: Cement paste has gel and capillary pores. The gel pores, which constitute more than 28% of the volume of cement paste, are very small and, in principle, their permeability is very low. What has a great influence on the permeability of concrete is the pores of the cement paste. If the cement paste contains only the water necessary for hydration, the volume of the porous pores in it reaches about 18% of the volume of dry cement (Maleki, M., *et al*., 2024) [25]. Capillary pores increase with the water-cement ratio increases and decrease with increasing hydration degree (Khanian, M., *et al*., 2013) [23]. Although increasing the number of capillary pores increases the permeability of the cement paste, the permeability coefficient is different in different cement pastes depending on the large passage paths between the capillary pores (Sadigh Sarabi, M., *et al*., 2023a).

The permeability coefficient increases significantly with capillary porosity of more than 35% or a water-cement ratio of more than 0.65. The permeability of concrete is one of its main disadvantages and the reason for its weakness in corrosive environments (Ghadarjani *et al*., 2013a). The penetration of water into concrete makes it weak in the freeze-thaw phenomenon, and the ingress of corrosive substances causes concrete to wash out and destroy the reinforcements (MM Norouzian & N Gheitarani, 2023) [27]. Acids with a pH of less than 4.5 have a strong corrosive effect on concrete, and concrete completely loses its resistance to strong acids. The flexural strength of concrete after exposure to corrosive environments is shown in Table 1. The water-cement ratio of the concrete mixture was 0.59, the flexural strength of the standard sample was 3.95 MPa, and the acid concentration in the test was 5% (Norouzian, M. M., & Sarabi, 2023) [33].

Table 1: Flexural strength of concrete in corrosive environments

Resistance Lost (%)	Average resistance after exposure to corrosive environment (MPa)	Corrosive environment
3/72	09/1	Acetic acid
2/77	9/0	Formic acid
4/2	86/3	Lactic acid
2/29	8/2	Sulfuric acid
29 (Increase)	56/5	Distilled water
25 (Increase)	27/5	Regular water

Introduction to Polymer and History of Use in Concrete: Definition of Polymer. By bonding a large number of small molecules called monomers (through covalent bonding), very large molecules called polymers are formed (Gheitarani, N., *et al*., 2024c). This process is called polymerization (Zakerhaghighi *et al*., 2015) [44]. Polymers are divided into two categories: Natural and synthetic polymer. Natural polymers refer to polymers found in nature (Ghadarjani *et al*., 2013b). Keratin, protein, cellulose, and starch are among the natural polymers. Synthetic polymers that are made in the laboratory by chemical reactions are themselves divided into two groups: Addition polymers***:***

The formation of bond between two molecules is created by breaking a double bond, such as polyethylene, and condensation polymers (Sadigh Sarabi, M., *et al*., 2024b). The polymerization of monomers is accompanied by the production of small molecules (such as water), such as polyesters. Each monomer in condensation polymers must have at least two active chemical agents (Dehghan S., 2024b) [6]. In the classification according to temperature, polymers are divided into two groups***:***

Thermoplastic (soft heat): Softens when heated and hardens when cold. These polymers have linear molecular chains that move relative to each other.

Thermoset (hard heat): Does not soften when heated, their network structure prevents the movement of polymer molecules. Characteristics that are examined in most polymers***:***

- Thermal properties: Polymer melting temperature (PMT), heat deflection temperature (HDT), polymer crystalline melting point (Tm), and polymer glass transition temperature (Tg)
- Average molecular weight 3- Degree of crystallization 4- Solubility spectrum 5- Proof of chemical structure in materials where there is uncertainty.
- Polymer Melting Temperature (PMT): The temperature at which a polymer melts and leaves no trace when gently moved across a hot metal surface.

Polymer Glass Transition Temperature (Tg): A polymer is a hard glass below a certain temperature and usually becomes soft or rubbery above that temperature (Gheitarani, N., *et al*., 2013a).

Thermal Deflection Temperature (HDT): The temperature at which a molded bar (0.5 x 0.5 x 125 to 0.5 in.) clamped at both ends when subjected to a temperature increase rate of 2 oC/min and a fiber tension of 66 or 264 p.s.i. Across the center of the bar, will deflect by 0.010 in. (Sohrabi, S., 2024b) [41].

Viscosity*:** There are several types of viscosity by definition**.** ***These include: Relative viscosity, specific viscosity, reduced viscosity, intrinsic viscosity, and intrinsic viscosity. All of these viscosities are calculated based on relative viscosity.

***Relative viscosity*:** The ratio of the time it takes for the polymer solution and the pure solvent to travel between the two marking lines in the viscometer.

t= Flow time for polymer solution
t0= Flow time for solvent

In other words, viscosity is defined as the resistance to flow (fluidity). The unit of measurement in this definition is the Poise or traditional Poise, and one of the measuring devices is the Brookfield viscometer (Karimimansoob, V. *et al*., 2024c).

***Solubility*:** Many polymers are soluble in organic materials. Usually, for new polymers, a range of solubility is defined after preparation. Polymers dissolve slowly due to their large size, and their solution is very viscous after preparation. The use of polymer solutions in the polymer materials manufacturing industry is extensive. Dissolving a polymer is one of the methods of shaping polymers.

Also, most of the properties of a polymer are obtained by dissolving it in a suitable solvent (molecular weight, average molecular weight, molecular size). As mentioned above, solvents reduce the viscosity of the polymer. Having a low viscosity for the polymer used in polymer concrete is very important because it not only facilitates mixing but also increases efficiency and makes its application easier. In selecting the solvent to be used in polymer concrete, in addition to having common criteria such as price, non-destruction of the polymer structure, and high solubility, criteria such as environmental effects, volatility rate, toxicity level, and flash point should also be considered (Gheitarani, N., *et al*., 2024b).

Of course, it is recommended that solvents should not be used in concrete production as much as possible. Cross-linking: Refers to cross-links between large polymer molecules. The creation of cross-links in the final curing stage causes the polymer to harden (Khanian, M., *et al*., 2019) [24]. The number of these links greatly affects the strength and elastic properties of the polymer. Equivalent weight: An equivalent means the mass of a substance that reacts with one mole of hydrogen (or one mole of electrons in an oxidation-reduction reaction). Epoxy equivalent weight is the mass of an epoxy polymer that has one reactive equivalent and is also called the mass of one mole of epoxy.

***Elastic properties*:** Increasing crystallinity and cross-linking increases the strength and hardens and stiffens the polymer, resulting in a decrease in elastic properties and ductility. For example, in CFRP fibers, increasing the curing temperature of the fibers increases the crystallinity in the fibers, increasing tensile strength and elastic modulus, but a decrease in the strain at break**.** Elastic materials have less cross-linking and an irregular structure.

3. Methodology

Among the common resins for preparing polymer concrete, epoxy was selected and used in preparing the samples. Unfortunately, manufacturers do not provide much information about the specifications of their products, and due to the lack of epoxy resins specifically for polymer concrete on the market, finding the right resin was a bit difficult due to the lack of specifications, including viscosity and epoxy equivalent weight. Finally, several types of epoxy resins and hardeners that were commercially available in the market were prepared. R 805 resin and its hardeners were purchased from Nasser Khosrow Bazaar in Tehran, and Dur 41 and Dur 42 resins were purchased from Namikaran Company (Sika). The specifications of the resins and hardeners are presented in Tables 2 and 3.

Table 2: Specifications of R 805 resin and hardeners used

Mixing ratio (by weight)	Setting time(hours)	Pot life (oc20)	Specific gravity	Color	Type	Brand name
		(minutes)	(g/cm3)	Colorless	Resin	R 805
100	2>	30>	15/1	Brown	Hardener	HA 12 (H_1)
12	4	60	02/1	Colorless	Hardener	5001 (H_2)

Table 3: Specifications of Dur 41 and Dur 42 resins and hardeners used

Mixing ratio	Setting time	Pot life (oc20) (minutes)	Specific gravity	Color	Type	Brand name
Resin: Hardener (by weight) 1:4	(hours) 2	30	(g/cm3)	White	Resin	Dur 41(A)
			18/1	Black	Hardener	Dur 41 (B)
1:6	2	30	02/1	Yellow	Resin	Dur 42 (A)
			12/1	Brown	Hardener	Dur 42 (B)

The hardeners used are diethylenetriamine or triethylenetetramine, which are in the aliphatic amine group. Due to their low price, the above materials are among the most common hardeners. Hardener 5001 has been modified by reducing the number of active hydrogens. Reducing the active hydrogen increases the equivalent weight of the hardener. Also, hardener HA 12 has been modified using cycloaliphatic amines.

Solvent: The solvent used was obtained by combining two common solvents for epoxy resin, namely acetone and toluene, in equal weight ratios. The specifications of the solvents are given in Table 4.

Table 4: Specifications of the solvents used

Solubility in water (g/l)	Viscosity (cp)	Boiling point (oC)	Melting point (oC)	Specific gravity	Solvent
0.47	59/0	6/110	95-	(g/cm3)	Toluene
Soluble	31/0	2/56	95-	866/0	Acetone

Stone materials: Two types of materials with different grain sizes were used in the preparation of the samples. The type of materials used is mentioned in Chapter 4 for each type of test. Since the dimensions of the manufactured samples are small, using materials with smaller grain sizes (Type 2) leads to greater convergence of the results obtained from samples made from the same mixing design.

There is no specific standard for the grain size of polymer concrete materials, and in the articles, only the passing of the materials through the 1 in sieve or the 4 number sieve is usually mentioned. The grain size of the materials used is given in Table 5. Type 2 materials are by the grain size of sand materials in the Iranian regulations (according to the British regulations). However, it is slightly different from the standard presented in ASTM C 33-03. Type 2 grain size has a large modulus of softness and, as a result, coarser grains (compared to the standard range). The reason for choosing such a grain size is to create the necessary efficiency in the polymer concrete in which the filler was used. As the grain size increases, the specific surface area of the material decreases and consequently the need for polymer also decreases.

Table 5: Grain size of the materials used in the manufacture of polymer concrete samples

Weight percentage rejected		**Sieve Score**	**Sieve size (mm)**
Type 2	**Type 1**		
100	100	in	5/9
100	77		75/4
8/75	2/51	4	36/2
9/51	6/27	8	18/1
2/31	6/16	16	6/0
9/15	9	30	3/0
5/4	1/4	50	15/0

The modulus of elasticity is usually calculated for fine-grained materials. The modulus of elasticity, bulk density, and apparent density (specific density) for type 2 materials were 3.21, 1.69, and 2.381 g/cm3, and the specific density for type 1 materials was 2.64 g/cm3.

Filler: Two types of fillers, rice husk ash, and broom stalk ash, were used for the first time in polymer concrete. The method and conditions for their preparation are described below.

Rice husk ash: The rice husk obtained from the Shalikubi factory was burned in the open air for approximately 48 hours. To burn a portion of the rice husk, a very small amount was soaked in kerosene to ignite it. After burning the rice husk depot, it was allowed to burn slowly (48 hours). Initially, the color of the husk becomes dark, but after burning a large amount of organic matter, its color tends to gray and white. It should be noted that the conditions of burning rice husk affect the ratio of the final ingredients. More silica is obtained within a certain temperature range.

Increasing the amount of silica in the ash used as an additive in cement concrete improves the pozzolanic property. However, in polymer concrete, the emphasis is on the filling property of the filler, although bonds can be formed between the filler and the polymer, which itself requires a separate investigation. After the rice husk is completely burned, the surface of the depot (which is not completely burned) is carefully removed and the ash inside is collected. Approximately 20 kg of ash is obtained from every 100 kg of rice husk. The ash obtained was placed in closed containers until consumption to prevent it from absorbing moisture. Also, to completely remove the unburned husks, the ash was passed through a 30-mesh sieve. The characteristics of rice husk ash are presented in Table 6.

Broom stalk ash: Broom stalks were placed in an open container for burning. Holes were made around the container to create airflow and better burning**.** The burning time of the stalks depends on whether they are fresh and moist or dry and old. Because they contain more organic matter than rice husks, the stalks burn faster. Dry stalks are completely converted to ash in less than half an hour, while fresh and moist stalks require a very long time (more than 6 hours). Finally, a direct flame was used to completely burn the stalks. About 15 parts of ash are obtained from every 100 parts of broom stalk by weight. To prevent moisture, the ash was stored in closed containers. Also, the ashes were passed through a 30-mesh sieve before use. The characteristics of broom stem ash are shown in Table 6.

Table 6: Physical characteristics of rice husk ash and broom stem ash

Specific surface area (Blain cm2/g)	Density(g/cm3)	Bulk density (g/cm3)	Type
3900	05/2	0.35	Rice Husk Ash
4400	16/2	0.27	Broom Stem Ash

How to prepare samples. Based on the calculated mixing ratios, the various components of the concrete are weighed. The resin and hardener are poured into disposable containers for weighing. When choosing disposable containers, care should be taken that they are not soluble in the resin and hardener. Resins and especially hardeners should not be left in the open air for a long time because there is a possibility of evaporation and absorption of moisture by them. After weighing, the resin and hardener are poured into the mixing container and stirred with a mixer for about 3 minutes. Then the filler is added in two stages and mixed well with the polymer for about 2 to 3 minutes. In the final stage, the stone materials are added in three stages and mixed with the polymer for about 3 to 5 minutes (Norouzian & Sarabi, 2023) [33].

The prepared mixture is poured into molds that have been cleaned and oiled in advance, and after the polymer concrete hardens, the molds are returned. Due to the effect of temperature on the properties of polymer concrete, it is better to store the samples in an oven at a temperature of 2∓ 23oC. The samples are ready for testing after seven days. In all stages of sample preparation and testing, the relevant standard conditions and limitations have been observed. It is important to pay attention to the following points in sample preparation***:***

An electric mixer should be used to mix the concrete components (especially resin-hardener).

The ambient temperature should be noted during mixing and testing

The materials should be mixed well for a sufficient period. It should be noted that the total time for mixing, molding, and troweling the materials should not exceed the time for polymer application.

The tools should be cleaned thoroughly after use and the molds should be opened.

Prepare a quantity of solvent (acetone or gasoline).

Use gloves during all stages of construction and take the necessary precautions when using chemicals.

Test Method: All tests and measurements were performed according to the American Standard (ASTM). The standard was selected based on the relevant test and the method was usually selected based on the size of the stone materials used. In the absence of a standard test for polymer concrete, the test was performed according to the cement concrete standard. The summary of the test method according to the relevant standard is as follows.

Specific Surface Area Test: The specific surface area of the grains was obtained using the ASTM C 204-00 standard. This test requires great precision during performance. The time it takes for a certain volume of air to pass through the test sample at an average pressure, where the airflow rate slowly decreases, gives the specific surface area when compared with the standard sample. The specifications of the standard sample are available from the NIST website. The apparatus includes a manometer tube, cylinder, piston, porous disk, filter, and hand pump to create suction, as well as some mercury and manometer liquid (dibutyl phthalate) required to perform the test. A very accurate balance (0.001 g) is used for weighing. Mercury is used for precise measurement of the volumetric space between the filters due to its very high specific gravity. The time it takes the liquid in the manometer to travel from the second to the third mark on the manometer gives the specific surface area using the following formula.

$$S = \frac{S_s \rho_s (b_s - \epsilon_s)\sqrt{\eta_s}\sqrt{\epsilon^3}\sqrt{T}}{\rho(b - \epsilon)\sqrt{\epsilon_s^3}\sqrt{T_s}\sqrt{\eta}}$$

S is the specific surface area (m2/kg), ρ is the density (g/cm3), T is the time in seconds, η is the air viscosity (µPa.s), b is a constant, Є is the porosity and the index s means the standard sample (for calibration).

Bulk density test (bulk density) for materials: The bulk density of the materials was calculated according to ASTM C 128-01. The materials were dried in an oven at 110 ± 5 C for 24 hours. By substituting the weight of the dry materials and the weight of the materials in the pycnometer in the following formula, the bulk density is calculated.

Apparent Density Test: This test was performed according to ASTM C905 Standard Method B. Cubic samples with dimensions of 50 × 50 × 50 mm were prepared, the method of preparing the samples is similar to the compressive strength test. Method II of the aforementioned standard was used to measure the density. The test method is as follows: The samples are completely dried, and their weight is measured in air and water. The bulk density is obtained from the following equation:

Dc = bulk density (g/cm3)
S = weight of the sample in air (g)
I = weight of the sample in water (g)

Modulus of elasticity: Due to the lack of a standard test for calculating the static modulus of elasticity of polymer concrete, this test was performed based on ASTM C 469-02, which is related to measuring the modulus of elasticity of cement concrete (although ASTM C 580 provides a method for calculating the secant modulus of elasticity). In some articles, cylindrical samples with a diameter of 76 mm and a height of 152 mm were used to calculate the modulus of elasticity. The dimensions of these specimens are smaller than those used to calculate the modulus of elasticity of cement concrete (150 mm diameter and 300 mm height) and require a fixed or hand-held mold and strain gauge of the appropriate size. Increasing the size of the specimen causes the heat released by the resin-hardener reaction to be trapped, and with increasing temperature, the setting time decreases (the strengths also change). The specimens were tested after 7 days of curing.

The force at a strain of 0.000050 and the strain at 40% compressive strength were recorded (usually several numbers are read in the approximate range of 40% compressive strength and then the numbers are interpolated). The modulus of elasticity is obtained using the following formula:

$$E = \frac{S_2 - S_1}{\epsilon_2 - 0.000050}$$

E: Modulus of elasticity (MPa)
S2: Stress based on 40% of maximum load (MPa)
S1: Stress read at 0.000050 strain (MPa)
e2: Strain read at S2 stress

Compressive strength test: This test was performed according to ASTM C579 standard method B by making cubic specimens with dimensions of 50×50 mm × 50. The molds were filled with the mixture in two stages, and after each stage, the sample surface was hammered. Finally, the sample surface was smoothed with a trowel. The samples were cured for 7 days at 23 oC and then their dimensions were measured by a micrometer with an accuracy of 0.025 mm. The range of changes (-3 and +1.5 mm) in dimensions is acceptable. The samples were subjected to a continuous force of 1.7 using a compressive strength device, and the maximum force was applied until the sample fracture point was recorded. The compressive strength is obtained from the following equation.

$$S = \frac{W}{L_1 \times L_2}$$

S = Compressive strength (MPa)
W = Maximum load (N)
L2, L1 = Cross-sectional dimensions of the sample (mm).

Single-point flexural strength test

The flexural strength test of polymer concrete was performed according to methods A and B of ASTM C 580-02.

According to the standard, for materials with a grain size smaller than 5 mm, samples with dimensions of 25×25×254 mm were made, and for materials with a grain size smaller than 10 mm, samples with dimensions of 50×50×310 mm were made. After 7 days of curing, the samples were tested. The loading rate was calculated based on the formula provided in the standard. The maximum force required to break the samples was recorded. The flexural strength is calculated from the following equation.

$$S = \frac{3\,PL}{2bd^2}$$

S = Stress at the center of the span (MPa)

P = Maximum force (N)
L = Distance between two load application points under the specimen (mm)
d = Specimen width (mm)
b = Specimen depth (mm).

Chemical resistance test: The chemical resistance test was performed according to ASTM C 267 standard method B. This test is a relatively quick method for evaluating the resistance of chemically resistant materials to attacks by corrosive environments. The basis of this method is based on changes in the specimen and the corrosive environment. The criteria for examining and evaluating the chemical resistance of materials in this method can be one of the following:
A- Change in sample weight (in the form of weight loss or gain).
B- Change in sample appearance (color change, surface cracks, swelling, peeling, softening, etc.).
C- Change in the appearance of the environment (color change, sediment, surface foam, etc.).
D- Change in sample compressive strength.

Cube samples were made according to the standard with dimensions of 50×50×50 mm. The method of making and storage conditions, as well as the dimensional accuracy of the samples, are similar to the standard for compressive strength testing. Then, a chemical solution with a specific concentration is prepared and the samples are placed in the desired chemical environment. The solution is poured in such a way that the samples are submerged in it. The samples can be tested after 1, 7, 14, 28, 56, and 84 days of exposure to the corrosive environment, and in these tests, the samples were tested after 7 and 14 days. Fresh solution must be poured into the container each time the test is performed. A balance with an accuracy of 0.001 g is required to record weight changes. In each examination, the appearance of the sample and the environment before and after the test, and the compressive strength of the sample before and after the test are compared.

$$\Delta_S = \frac{S_2 - S_1}{S_1} \times 100$$

sΔ = Percentage change in compressive strength
S1 = Average compressive strength of reference samples
S2 = Average compressive strength of samples after exposure to a corrosive environment

$$\Delta_W = \frac{W - C}{C} \times 100$$

ΔW = Percentage change in sample weight
C = Reference sample weight
W = Sample weight after the test

4. Findings
To get acquainted with polymer concrete and the effect of concrete mix preparation conditions and the effect of aggregate grading on polymer concrete properties, several compression specimens were prepared and tested. In these tests, epoxy resin R 805, hardener 5001, and type 2 stone materials were used. In the first step, the mixing time of resin-hardener and polymer materials was investigated. The results showed that 3 minutes of mixing is sufficient for resin hardener and 3 to 4 minutes for polymer materials. Of course, depending on the viscosity of resin and hardener or the efficiency of the concrete mixture, it can vary to some extent. The method and quality of adding stone materials to the polymer mixture were used in two ways:

- The gradual addition of materials that passed through a 4-point sieve (in three stages).
- First, materials that passed through a 30-point sieve (clays and clays), and then the remaining materials on the sieve were examined.
- The compressive strength obtained for method 1 was 69.5 MPa and for method 2 was 71.12 MPa.
- The almost equal strengths obtained in addition to showing the correctness of mixing by method 1 confirm that the polymer and materials are well mixed together within the mentioned time.
- The effect of material grading was also briefly examined.
- The results are presented in Table 7.
- The samples contained 18.4% polymer.

As can be seen, changing the material grading does not have much effect on the compressive strength of the tested samples, but it greatly changes the efficiency of the mixture. Due to the higher specific surface area of the materials passing through the 16-gauge sieve, the prepared mixture was less efficient than the samples made from other materials. By removing the fine particles, the polymer and materials are separated. As a result, polymer concrete may show more severe resistance changes in high volumes of the mixture.

Table 7: Effect of material grading on compressive strength

Materials passed through a 4-gauge sieve and remaining on a 16-gauge sieve	Material passed through a 16-gauge sieve	60% of the material passed through the 16-gauge screen + 40% of the material remaining on the screen	Compressive
8/66	2/68	7/69	**Strength index (MPa)**

Studying the effect of hardener-resin mixing ratio on the strength of polymer concrete In these experiments, Dur 42 resin and type 1 materials were used in the manufacture of samples. The amount of polymer added is 15% of the weight of the concrete (the ambient temperature at the time of sample manufacture is between 30 and 32 degrees Celsius). According to the discussions discussed in the second chapter, the mixing ratio (hardener resin) is calculated based on stoichiometric ratios. Usually, resin manufacturing companies determine the mixing ratio and provide it to buyers. The mixing ratio of hardener-resin Dur 42 is presented in Table 7.
In addition to the above ratio, four other mixing ratios were also used in the manufacture of samples. Fig 1 and Fig 2. Show the values of compressive and flexural strengths obtained from the tests. According to the results obtained, reducing the hardener-resin ratio increases the strength, and increasing the hardener-resin ratio from the recommended

value reduces the compressive and flexural strengths. Also, reducing the hardener-resin ratio (approximately 5%) greatly reduces the strengths. The elastic modulus of polymer concrete samples for ratios of 10%, 16%, and 22% are given in Table 7.

The elastic modulus also shows similar changes. An increase in the strength and elastic modulus of polymer concrete is an indication of an increase in crosslinks in the polymer, which increases the hardness and reduces the ductility of polymer concrete. A change in ambient temperature can affect the mixing ratio, especially in the case of amine hardeners. An increase in temperature causes a decrease in the mixing ratio. One of the reasons for the decrease in the mixing ratio in this study could be the high ambient temperature during mixing. One of the factors affecting the decrease in the mixing ratio is an increase in the mixing volume. As a result, it is better to check the accuracy of the proposed mixing ratio before conducting the tests. Such changes in strength can be considered both an advantage and a disadvantage of polymer concrete, which can create changes in the mechanical and chemical properties of polymer concrete as needed without changing the type of polymer or the polymer-material ratio.

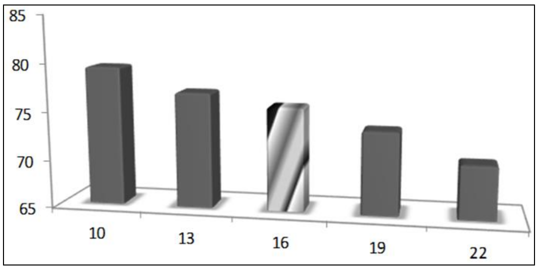

Fig 1: Compressive strength of samples with different hardener-resin mixing ratios

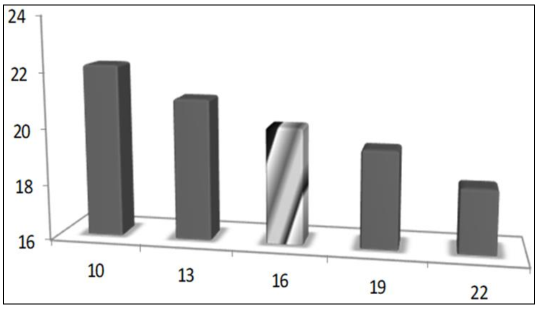

Fig 2: Flexural strength of samples with different hardener-resin mixing ratios

Table 8: Modulus of elasticity of polymer concrete with different hardener-resin ratios

Hardener-Resin Ratio *(%)*			Characteristic
22	16	10	
71/23	12/25	93/26	**Modulus of elasticity (GPa)**

5. Results

Effect of hardener type on polymer concrete properties: According to the previous explanation, the hardener type greatly affects the properties of the hardened polymer and consequently the properties of polymer concrete. To demonstrate the hardener effect, samples were made from the same type of epoxy resin and with the same materials but with two different types of hardeners. In this test, epoxy resin R 805 and hardeners HA 12 (H1) and 5001 (H2) as well as type 2 stone materials were used. The results of the compressive and flexural strength tests are shown in Fig 3 and Fig 4.

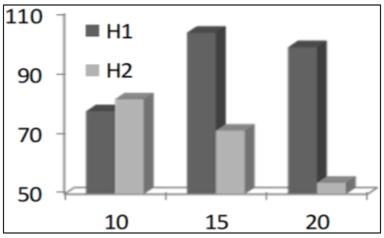

Fig 3: Compressive strength of polymer concrete with two different types of hardeners

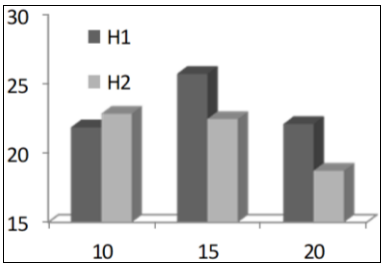

Fig 4: Flexural strength of polymer concrete with two different types of hardeners

Investigation of the effect of solvent. Two types of resins Dur 41 and Dur 42 and type 1 stone materials were used in the manufacture of the samples. The samples were made with 8 and 10% polymer. The resins were mixed with a solvent (acetone-toluene (50%-50%)) before use to reduce the viscosity. Because there is no specific method for determining the efficiency of polymer concrete mixtures and common methods for cement concrete such as slump test, compaction factor, flow table, and hemispherical penetration require a high volume of mixture. They are not suitable for the volume of polymer concrete made in this experiment. Therefore, Vicat needles with a diameter of 1 mm and 1 cm were used for comparison. The penetration value of the needle was measured for 30 seconds.

Also, the penetration value of a 1 cm Vicat needle was recorded by adding a 1 kg weight for 5 seconds. The results show that generally adding solvent increases the needle penetration rate. However, in concrete containing Dur 42 resin (the viscosity of Dur 42 resin is lower than Dur 41 resin), no change in the Vicat needle penetration rate is observed with increasing the solvent-to-resin ratio from 0.05 to 0.1. Adding solvent to polymer concrete consisting of Dur 41 resin increases the specific gravity of the concrete. However, adding 10% solvent to polymer concrete made of Dur 42 resin decreases the specific gravity. Increasing the percentage of polymer increases the specific gravity of polymer concretes made of both types of resins.

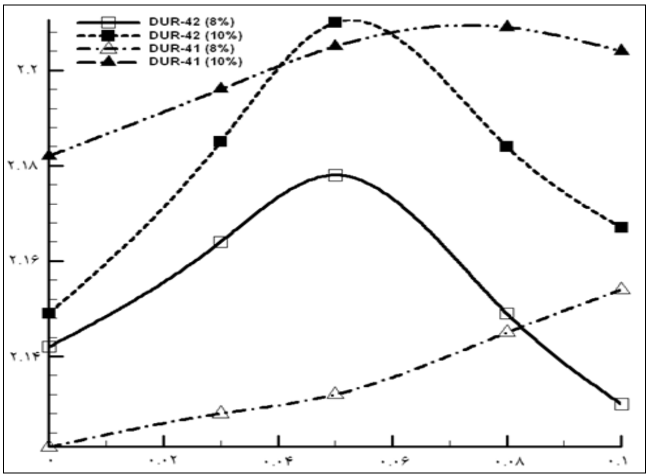

Fig 5: Effect of solvent on the specific gravity of polymer concrete

Even with the relatively low viscosity of Dur 42 resin, as can be seen, adding 5% solvent increases its compressive and flexural strength, which is greater at a resin-to-aggregate ratio of 10% (about 26% increase in compressive strength and 16% increase in flexural strength). As shown in the figure, increasing the percentage of polymer improves compressive and flexural strength in resins with higher specific gravity (Dur 41). Increasing viscosity reduces surface tension in polymers. Reducing surface tension increases polymer penetration into aggregates and underlying surfaces.

6. Conclusion

In this study, various experiments have been conducted to investigate the factors affecting the mechanical and chemical properties of polymer concrete. It should be noted that the results obtained, which are presented below, can be a guide for using polymers in polymer concrete in practical applications. Therefore, considering the different characteristics and properties of different polymers as well as different environmental conditions, the necessary tests should be performed to obtain accurate resistance values and the optimal amount of polymer. The results obtained can be summarized as follows:

- The compressive strength of polymer concrete is several times that of cement concrete. The maximum compressive strength obtained in this study was 103.8 MPa. The compressive strength is affected by the type and amount of polymer, hardener, and additives.
- Replacing cement with polymer causes a significant increase in flexural strength.
- The maximum flexural strength obtained from the experiments was 29.17 MPa.
- Factors affecting compressive strength also affect flexural strength, but their optimal values can vary.

One of the characteristics of polymer concrete is the lower ratio of flexural to compressive strength. The specific gravity of polymer concrete is lower than that of cement concrete (1.8 to 2.32). Due to the lower modulus of elasticity of the polymer compared to the materials, increasing the percentage of polymer reduces the modulus of elasticity of polymer concrete.

- The modulus of elasticity of polymer concrete and cement concrete does not differ much from each other.
- The type of resin and hardener greatly affects the properties of polymer concrete.
- The use of two different types of amine hardeners caused 27 and 13 percent changes in the maximum compressive and flexural strengths of polymer concrete.
- By changing the hardener-resin mixing ratio, hard concrete with a high modulus of elasticity or ductility can be obtained.

Adding rice husk ash and broom stem ash as fillers to polymer concrete showed that:

1. Adding filler can improve compressive and flexural strengths.
2. Increasing the amount of filler increases the modulus of elasticity.
3. The amount of filler's effect on concrete properties is affected by the percentage of polymer.
4. Concretes containing fillers show better chemical resistance.
5. Specific surface area can be an important distinguishing factor in the induced properties of fillers on concrete.
6. Both types of fillers used (rice husk ash and broom stem ash) had almost similar effects on polymer concrete. Adding solvent can improve the efficiency of the mixture by reducing the viscosity of the resin.

Adding optimal amounts of solvent improves the density of the mixture (specific gravity) and increases compressive and flexural strengths. Polymers have been used in developed countries for decades to improve the properties of concrete. Although extensive research and studies have been conducted on polymer concrete in these countries. However, to become familiar with the properties of concrete and considering the different climatic conditions and climates and polymer raw materials available in the country, the need for extensive studies and research in this field is felt. In this research, some of the mechanical and chemical properties of polymer concrete as well as the factors affecting it have been studied and investigated. The following suggestions are made for future research:

- Investigation of the effect of polymer
- Use of other types of polymers such as polyester, polymethacrylate, furan, etc. in the manufacture of polymer concrete.
- Investigation of the effect of molecular size, equivalent weight, number of functional groups, glass transition temperature, thermal deflection temperature, etc. of resin on the properties of polymer concrete.
- Investigation of the effect of the type and amount of hardeners as well as curing conditions (at room temperature or higher temperatures) on the properties of polymer concrete.

Investigation of the effect of aggregate:
Investigation of the effect of the type and size of aggregates on the strength properties of polymer concrete investigation of the effect of aggregates on the weight and appearance of polymer concrete. Investigation of the effect of additives:

- Use of additives including surfactants, plasticizers, anti-bubble, solvents, and diluents, etc.
- Use of fibers and rebars (metal, carbon) in improving the properties of concrete (also an investigation of the interaction of the matrix of FRP rebars with the polymer binder).

- Use of Various fillers such as consumer, industrial, and agricultural waste.

Experiments and research:

- Making samples in large pieces for optimized quantities and comparing their behavior with cement concrete.
- Conducting tests such as abrasion, impact, damping, and corrosion as well as simulating the above tests (e.g. for road transportation).
- Localization of polymer concretes based on the climatic and environmental conditions of different regions of the country.
- Comparison of commercial brands of resins that can be used in concrete and modifying its properties for use in a specific project.
- Conducting studies on the economic and environmental aspects of polymer concrete.
- Using polymer concrete in building industrialization (manufacturing prefabricated parts).
- Study and research on polymer-cement concrete and injected polymer concrete, each of which has a wide field of application.

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